Investigating the Voltage Response of a Piezoelectric Crystal using TV Holographic Techniques

Alexander Stansfield
10626406
School of Physics and Astronomy
University of Manchester
The experiment was performed in collaboration with Ryand Yandoc
(Dated: November 5, 2022)

By connecting a piezoelectric (PZT) crystal to a rotating screen and applying a TV holographic technique to measure the deformation of the screen and infer the voltage response of the PZT crystal, which was determined to be $5.96 \pm 0.07 \times 10^{-7}\mathrm{mV}^{-1}$.

I. INTRODUCTION

Searching and analysing deformations is vital to determine the integrity and stability of materials. TV Holography is an example of a non-destructive technique that uses optical interferometry to detect and measure deformations.

In this experiment, a Piezoelectric (PZT) actuator creates linear deformation across the surface of a screen. When a potential difference is applied, the PZT crystal will expand. This deformation then displaces an aluminium screen, from which we can infer the PZT actuator voltage response.

II. THEORY

Holographic techniques require two coherent beams: an object beam (directed towards the deformed material) and a reference beam (directed towards a screen whose position remains constant throughout the experiment).

The path difference between the object and the reference beam will change when the material deforms, thus the interference between the two beams.

In the case that the material's surface is non-specular, one can take the absolute difference in intensities of images before and after deformation and observe "fringes". These fringes arise due to areas of high and low correlation between the two pictures.

An ideal form of deformation to analyse these fringes with would be linear deformation, where the deformation of the screen $d(x)$ is linearly proportional to the position of the screen x, Eq. 1, as depicted in Figure 1.

$$d(x) = \frac{D}{X}x \tag{1}$$

The phase difference between the object and reference beam can be calculated with Eq. 2.

$$\Delta\phi = \frac{2\pi}{\lambda}2d(x) \tag{2}$$

Eq.3 [1] analyses the behaviour of the fringes by relating the spacing between the observed fringes and the change in phase difference in the x-direction.

$$\Delta x = 2\pi\left(\frac{\partial\Delta\phi}{\partial x}\right)^{-1} \tag{3}$$

From Eq. 1, 2 and 3, we can relate the maximum deformation of the screen and the subsequent spacing between the fringes as Eq. 4, indicating an inverse relationship between deformation and fringe spacing.

$$D = \frac{\lambda}{2}\frac{X}{\Delta x} \tag{4}$$

If we make the assumption that there exists a linear relationship between the angle of the screen and the voltage supplied to the PZT, we can find the voltage response of the PZT crystal. To do this, we plot the inverse of the fringe spacing against voltage and convert it to displacement with Eq. 4.

In order to obtain the object and reference beam required, we used a Michelson interferometer-inspired setup, as shown in Figure 2. We used a HeNe laser to produce coherent light at a wavelength of 632.8 nm and

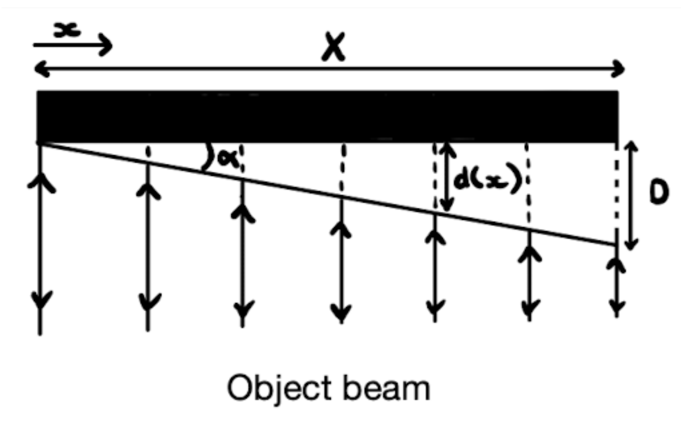

FIG. 1. Schematic showing the linear deformation of the screen.

concave lenses to diffuse the beam across the screens' surfaces. The beam splitter splits the laser light at a 90° angle towards the rotated aluminium screen (the object beam) and the stationary aluminium screen (the reference beam).

It is essential to use a non-specular surface so that the macroscopic beams do not obey the law of reflection, otherwise, the deformation will reflect the object beam away from the camera. When a non-specular surface is used for coherent beams, the light interferes locally on the screen surface. This process forms a phenomenon known as a "speckle pattern", where areas which constructively interfere form bright spots, whereas those which destructively interfere form dark spots. Once these two speckle patterns are reflected towards a camera, a resultant interference pattern is formed (i.e. a hologram).

The resultant speckle pattern between an image taken before and an image taken after deformation was only similar in the regions where the is a phase difference $\approx 2n\pi$. Otherwise, the speckles differ and form a "low-correlation" region. Thus, by taking the difference between these two images, these regions remain bright as the two speckle patterns do not cancel out. Eq. 3 describes the distance between low-correlation regions.

III. METHOD

A digital camera took an initial reference image when a potential difference of 0V was created across the PZT crystal. The voltage was then immediately raised by 5V, and the next image was taken 30 seconds later. These steps were repeated up to and including 60V. At that point, the voltage was decreased in increments of 5V back to 0V.

A software called ImageJ [2] processed the images by subtracting two images from each other and obtaining the graph of intensity against distance. An example is shown in Figure 3.

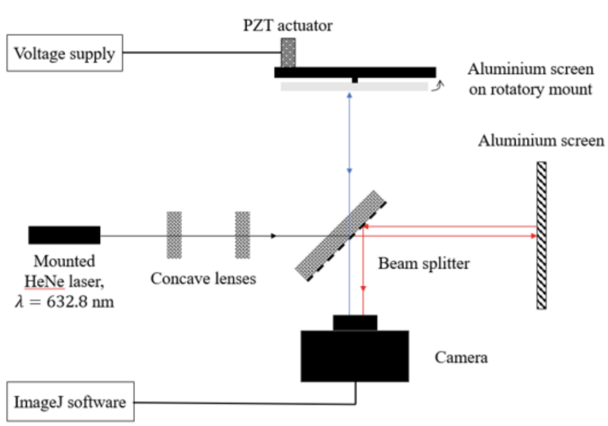

FIG. 2. Schematic showing the setup of the experiment. A Canon EOS 1100D digital camera was used. Red arrows indicate the reference beam and blue arrows indicate the object beam.

The raw data was then passed through a high-frequency filter to reduce noise. The Savitsky-Golay filter [3] (filter often used in signal processing [4]) was chosen as it was easy to fine-tune the filter's associated parameters to maintain the core structure of the interference pattern.

An estimate for the fringe spacing was calculated by taking the average of the resultant peaks. The raw data around the peak was fitted with a Gaussian curve, using half the estimated fringe spacing as the range of raw data fitted. Using the Gaussian fit resulted in more accurate estimates of the location of the peaks along with an associated uncertainty value. The final value of the fringe spacing was taken to be the weighted arithmetic mean of the difference between neighbouring peaks.

A conversion factor had to be calculated to convert our measurements from pixels (the unit of length the camera uses) to metres. This factor was calculated by taking a picture of the screen with a ruler placed across it. For our experiment, the scale factor was 465 ± 11pix m^{-1}.

Eq. 4 was used to convert the inverse of the fringe spacing to the screen deformation. Figure 4 shows a plot of the final calculated values against the voltage.

IV. RESULTS

The voltage response of the PZT actuator was observed to be generally linear between 10V and 50V, as predicted by Eq. 4. Moreover, the increasing and decreasing gradients were within three standard deviations of each other, suggesting an almost identical linear response of the PZT in both cases.

However, the calculated chi-squared was within the range of 1.5-0.5 for only one of the plots, this suggests that there may be some underlying non-linearity in the experiment. Furthermore, there is an apparent hysteresis evidenced by the different y-intercepts, which we believed was due to the actuator's response being non-linear

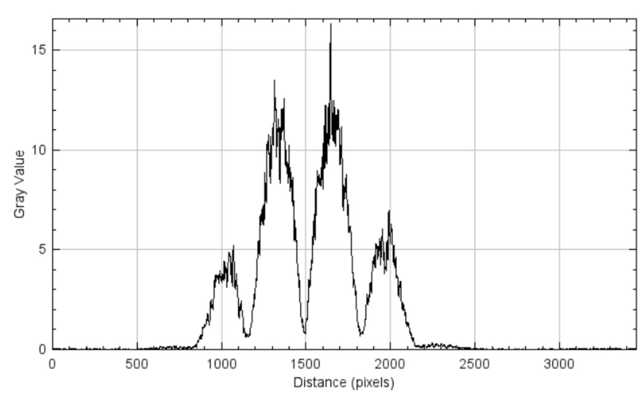

FIG. 3. Resultant intensity pattern when the absolute difference between the images taken at 0V and 20V was processed with ImageJ. The fringes, i.e. the peaks, are evident.

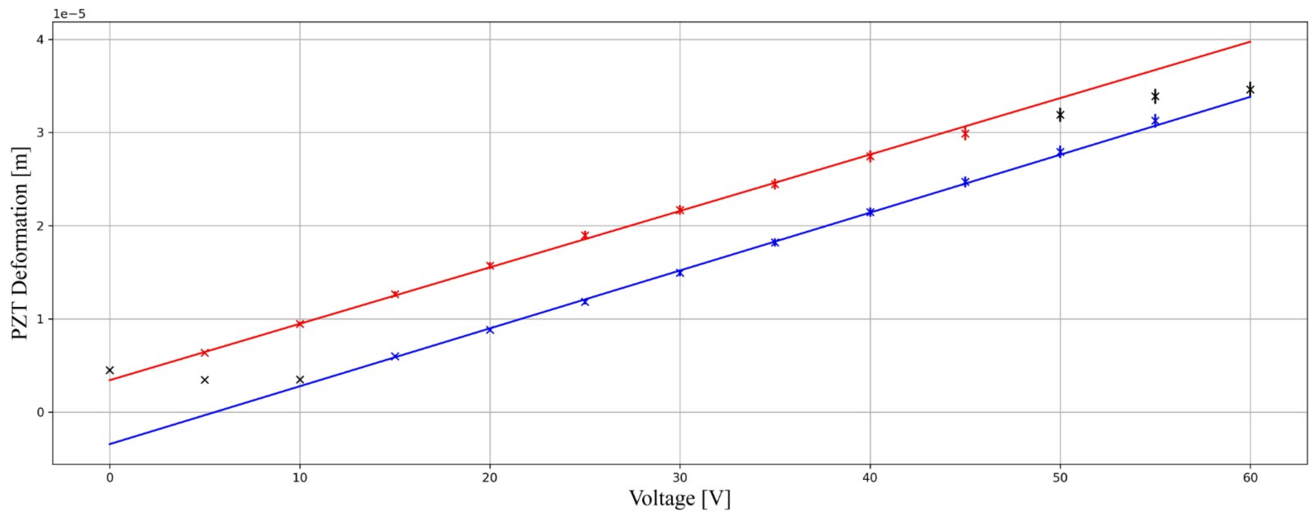

FIG. 4. Final plot of maximum deformation of the screen in metres against the voltage supplied to the PZT crystal. The line of best fit was made for points which followed a linear trend; the points highlighted were used in the fit.

when we changed the voltage, i.e. when $\frac{d^2V}{dt^2} \neq 0$. There appeared to be a "response time" when we change the voltage "from rest" (0V) and when going from increasing to decreasing voltage. Thus we excluded the points which did not appear to follow the linear trend visually. Moreover, if the voltage exceeded 60V, no fringes were visible when decreasing the voltage back to 0V. Since this appeared to be a consistent occurrence, the irregularity may have been caused by the erratic behaviour of the crystal itself, possibly due to a temperature increase and non-linear thermal expansion.

However, no measurements could be made when deformations were larger than around 40μm. At this point, the noise caused by random changes in the speckle pattern over the camera's exposure time was comparable to the fringe spacing. Therefore, it was impossible to differentiate peaks which were part of the core interference pattern and "false peaks" arising from noise.

Over all of the runs and for data within the perceived linear region, the average voltage response was found to be $5.96 \pm 0.07 \times 10^{-7}$mV^{-1}.

V. CONCLUSION

In conclusion, the PZT actuator generally has a linear relationship with the voltage supplied. Minor deviations from the linear relationship are most likely due to external factors, such as the added thermal expansion at higher temperatures and the response time of the PZT actuator.

The experiment was limited by the noise of the speckles. Moreover, it was challenging to have the PZT actuator have consistent behaviour since it appeared that minor temperature changes would result in a different voltage response.

All obtained values for the gradients of the line of best fit agreed with each other to three standard deviations. However, most runs were scrapped when taking the final average due to inconsistency and lack of fringes in the processed images.

[1] R. Jones and C. Wykes, Speckle pattern interferometry, in *Holographic and Speckle Interferometry*, Cambridge Studies in Modern Optics (Cambridge University Press, 1989) p. 122–164, 2nd ed.

[2] W. Ferreira and W. Rasband, ImageJ User Guide (2012).

[3] A. Savitzky and M. J. E. Golay, Smoothing and differentiation of data by simplified least squares procedures., Analytical Chemistry (1964).

[4] G. N.B., Savitzky-golay smoothing and differentiation filter, Eigenvector (2020).